3.13 Multipath/Diffraction Validation

Summary of Results

Two test cases have been completed for validation of the multipath/diffraction FE.

The results of the first test are inconclusive, due to inaccuracies in the measurement of the target altitude during field testing. Nevertheless, a few problems with the ALARM implementation of the multipath/diffraction FE were found during validation testing. Section 3.0 discusses the Model Deficiency Reports concerning multipath/diffraction that have been submitted to the Model Manager for review.

The second validation test, a comparison of measured and modeled one-way pattern-propagation factors, indicates significant differences, particularly as a function of the method chosen by ALARM to determine the one-way pattern-propagation factors. The overall impact of these differences on the prediction of maximum target detection is significant if a clear line-of-sight exists between the radar and the target. If the target is masked from the radar, the impact is insignificant.

FE Description

As a radar signal travels to and from a given target, the signal is attenuated by near-earth propagation losses attributed to the combined effects of refraction, multipath, and diffraction.

Refraction is the bending of the radar wave as it passes through a non-homogeneous medium having varying dielectric constants. The atmosphere is one such non-homogeneous medium, having a decreasing dielectric constant as the atmosphere becomes less dense with increasing altitude. The decreasing dielectric constant causes the wave to bend toward the earth increasing the path length relative to direct line-of-sight path length. The increase in path length is often approximated by assuming the earth’s radius to be four-thirds the nominal earth’s radius. Similarly, the radar horizon is extended by the refraction effect and is estimated using the four-thirds earth radius approximation. Because of the increase in path length, due to refraction, the propagation losses increase proportionately relative to the direct line-of-sight path length.

Multipath losses are the result of the reception of the radio frequency signal over two or more distinct paths identified as: 1) the direct path from the radar to the target, and 2) one or more reflected paths from the radar to the earth to the target. The distance of the direct path and the reflected paths are different, resulting in differences in phase and amplitude of the signals reaching the target. Depending upon the path length differences, the direct and multipath signals may tend to cancel or reinforce the signal received along the direct path.

Diffraction is the phenomenon which causes a radar wave to bend when it passes over or around an obstruction. Typically diffraction is considered to be either spherical earth diffraction, which is the bending of the radar wave when passing over smooth round earth, or knife edge diffraction, which is the bending of the radar wave around an obstruction such that it fills the shadow behind the obstruction.

Near-earth signal propagation effects are typically considered to include multipath, diffraction, and combined diffraction and multipath which occur in three defined regions. These regions are known as

1. the interference region, where the target is well above the horizon and where multipath is predominant;

2. the intermediate region, where the target is along the line-of-sight path to the horizon where both multipath and diffraction occur; and

3. the diffraction region, where the target is below the horizon and only diffraction effects can occur.

To simulate the effects of multipath and diffraction on signal propagation, ALARM incorporates the SEKE model developed by the MIT Lincoln Laboratory. The model SEKE is based on the assumption that the propagation loss over any path at the microwave frequencies of interest (VHF to X-band) can be approximated by one of the multipath, multiple knife-edge diffraction, or spherical earth diffraction losses or a weighted average of these three basic losses. The proper algorithm is selected based on the terrain elevation data for the propagation path, the altitude and range of the target, and the radar frequency. Figure 3.13-1 summarizes the guidelines of the model. The model is described in detail in *SEKE: A Computer Model for Low-Altitude Radar Propagation Over Irregular Terrain, Project Report CMT-70* [A.2-3].

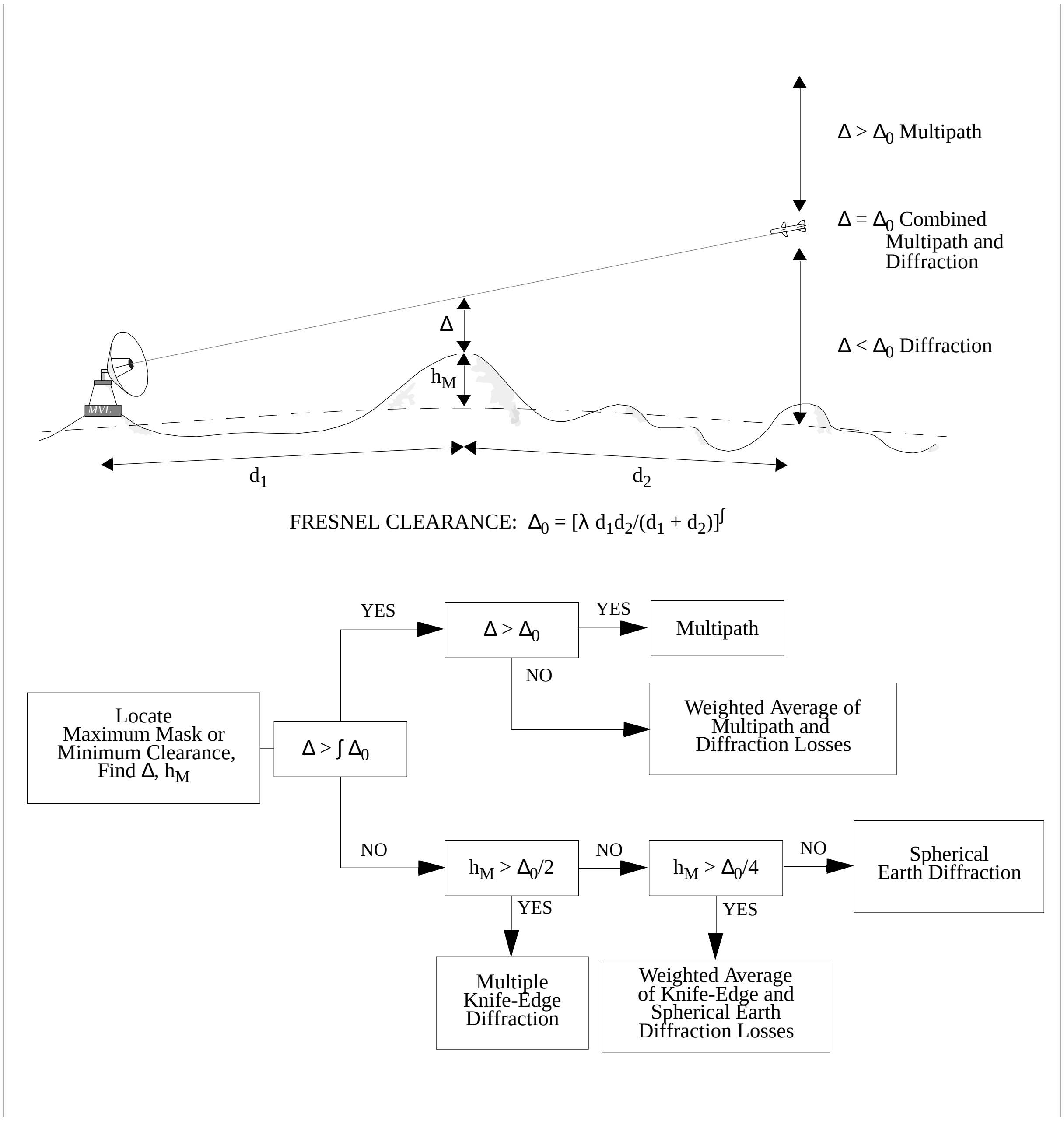

Figure 3.13-1 Guidelines of the SEKE Model

3.13.1 ATCOM/AATD SPAR Model Validation Test

Validation Objective: The objective of the test was to measure the effect of multipath propagation on received target signal strength and to compare the measured multipath propagation with the modeled propagation.

Measures of Effectiveness: Two measures of effectiveness (MOEs) were selected for comparison of measured and model-predicted multipath propagation effects on the target signal:

1. the mean and standard deviation of the difference between measured and model-predicted multipath propagation loss for identical conditions of test, and

2. the number of target detections along the test flight path as a function of target RCS for modeled and measured multipath propagation loss.

A perhaps more desirable MOE, a comparison of initial target detection range using measured and modeled propagation, could not be evaluated since the test target flight profiles were limited to a single profile with the target always within the detection envelope.

Test Description: Boeing Helicopter conducted a series of tests from October 1991 through April 1993, under contract with US Army Aviation and Troop Command (ATCOM) Aviation Applied Technology Directorate (AATD), Fort Eustis, VA, designed to collect data for the validation of the Boeing radar detection model, Signal Processing of Radar (SPAR). The SPAR model includes the Lincoln Laboratory algorithms collectively called SEKE (Spherical Earth/ Knife Edge Diffraction), which is also used in ALARM.

The Boeing-AATD test program included instrumenting several radars located on or near the beach at the Eglin AFB test range, and collecting signal and environmental data during some specially designed helicopter test flights. Boeing then analyzed the recorded data, using those data to assess the SPAR model. The tests and analysis are documented in *USAATCOM TR 93-D-3, Threat Radar Operational Verification*. Of the test missions flown, two were of specific interest to the SMART functional element validation process:

1. A UH-60A helicopter was equipped with a 22 dBsm corner reflector, and flown along in-bound radial flight paths toward the site at an altitude of 10.0 meters and a speed of 70.0 knots, and

2. The corner-reflector equipped helicopter was flown along the same flight path at an altitude of 20 meters.

Specific data recorded at the radar included target range, calibrated received target signal level, radar elevation angle, and Global Positioning System (GPS) derived target altitude.

Data Description: The data collected during the test and analyzed for comparison to modeled multipath propagation included:

1. Received target signal strength - The signal strength was measured at each received pulse for a 100 msec period of time during a 1.0 second data block. The signal strength was recorded in dB referenced to the signal strength of a one square meter radar cross section (RCS) target.

2. Target range and altitude - The recorded target range was the radar measured target slant range and the target altitude was measured using incremental GPS.

3. RCS enhanced target signature - The azimuth plane RCS of the corner reflector, carried aboard the target helicopter to create a constant RCS target, was measured and recorded.

4. Radar antenna elevation angle - The target track radar used during the test automatically tracked the target. The radar antenna elevation angle was recorded throughout the test runs.

5. Radar coordinates and antenna height

6. Sea state

Data Processing: The original target signal data were recorded pulse-by-pulse in pulse time order. However, individual data were not always available in descending range order, perhaps due to the range resolution or tracking of the test radar. A software program was created to average the signal data into unique range bins and then sort by range. The resultant files were then converted to ALARM format input text files, including generating an artificial latitude/longitude for target position along the flight path. ALARM was modified to accept location data at accuracies of one tenth of an arc-second (approximately ±3 m). Additional model inputs were prepared to simulate the parameters of the actual radar system under test. A measured antenna gain pattern for the test radar was not available, so a two-dimensional antenna gain pattern input data set was synthesized using nominal intelligence data for the radar type. Source code modifications were made to calculate and record the clutter signal and multipath propagation factor. The target flight path was known to be a constant altitude, radial path over water. Only the range to target and target altitude were recorded; the actual latitudinal and longitudinal positions of the target were not recorded. ALARM requires the latitude and longitude position target coordinates as target flight path input parameters. Since the flight path was entirely over water with no intervening terrain, the range to target was converted to latitude and longitude along an arbitrary radial flight path.

The recorded signal included both the target and sea clutter reflected signals. Since the contribution of clutter to the composite signal could not be measured directly, the effective clutter RCS was approximated at each range increment and subtracted from the measured signal level, which was recorded in dBsm.

The testers at Eglin AFB recorded the received target signal by referencing it to a known signal of a one square meter RCS target, using the ratio S_n to S_r, where S_n is the measured signal and S_r is the reference signal. In addition, the signal also included both the target (σ_r) and clutter (σ_c) RCS values. The validation of the ALARM multipath FE required derivation of the measured multipath propagation loss from the test data using the equations defined below.

The reference signal (S_r) used for calibrating the target signal is measured at some range (R_r) for a constant RCS (σ) target. The reference signal can be expressed as:

$$S_r = \frac{P_t G_t G_r \lambda^2 \sigma_r}{(4\pi)^3 R_r^4} \tag{3.13-1}$$

where
- P_t = peak transmit power
- G_t = transmit antenna gain
- G_r = receive antenna gain
- λ = wavelength of radar
- σ_r = target RCS
- R_r = slant range to target

The above assumes that the target is at an altitude such that the multipath and clutter effects are negligible.

The signal level measured at any other range (R_n) can be computed as:

$$S_n = \frac{P_t G_t G_r \lambda^2 (\sigma_r + \sigma_c) F_m}{(4\pi)^3 R_n^4} \tag{3.13-2}$$

where
- F_m = multipath factor
- σ_c = clutter RCS = σ_o x patch area
- R_n = slant range to target

From (3.1-1) and (3.1-2) above, the following relationship can be derived from the ratio of S_n to S_r:

$$(\sigma_r + \sigma_c)F_m = \frac{R_n^4 S_n \sigma_r}{S_r R_r^4} \tag{3.13-3}$$

Let

$$K = \frac{\sigma_r}{S_r R_r^4} \tag{3.13-4}$$

Then

$$(\sigma_r + \sigma_c)F_m = R_n^4 S_n K \tag{3.13-5}$$

The multipath factor in dB can be expressed as:

$$F_m = 40\log_{10}(R_n) + 10\log_{10}(S_n) + 10\log_{10}(K) - 10\log_{10}(\sigma_r + \sigma_c) \tag{3.13-6}$$

For the test as conducted, the values of R_r, R_n, σ_r, S_r, and S_n are measured values, and the data is plotted as $(\sigma_r + \sigma_c)F_m$ vs. R_n. To arrive at an accurate value of the multipath factor, it is necessary to compute the equivalent clutter RCS at each range increment. Then the measured value of the multipath factor, expressed in dB, will be:

$$F_m = \text{Measured test signal} - 10\log_{10}(\sigma_r + \sigma_c) \tag{3.13-7}$$

The above process will accurately determine the multipath factor if the target is always in the radar antenna boresite. However, it was observed that the antenna boresite was not always on the GPS target elevation. This would result in a decrease in target signal level which would appear as a decrease in the multipath factor. Additionally this would lead to an error in computing both the ALARM multipath factor and clutter signal return. The error in target signal can be corrected by computing the relative antenna gain in the direction of the target. The corrected target RCS will then be:

$$RCS_{cr} = 158.489 * G_t(\Theta) * G_r(\Theta) \tag{3.13-8}$$

where

where	158.489	=	the target RCS in square meters
	$G_t(\theta)$, $G_r(\theta)$	=	the absolute value of the antenna transmit and receive gain in the direction of the target relative to the boresite antenna gain

Finally, the measured value of the multipath factor is given by :

$$F_m = \text{Measured signal} - 10\log_{10}(\text{RCS}_{cr} + \text{RCS}_{cl}) \tag{3.13-9}$$

where RCS_{cl} = clutter patch reflective area

Analysis Procedures: The procedure for comparing the measured multipath propagation loss to ALARM-predicted multipath propagation loss is as follows:

1. Modify ALARM to accept antenna elevation pointing angles as a function of target range.

2. From the measured antenna elevation data, compute antenna elevation angles as a function of target range.

3. Using ALARM, modified to accept the antenna pointing angles, compute the absolute value of the antenna gain in the direction of the target relative to the boresite gain at each range increment.

4. Using the absolute values of antenna gain in the direction of the target, compute the target signal RCS at each range increment. The adjusted RCS is given by equation (3.1-8).

5. Using modified ALARM, compute the clutter RCS at each target flight path point, where the clutter RCS is summed over all terrain patches along the current radial to the target and can be expressed using ALARM variables as:

$$\text{CLTRCS} = \text{CLTRCS} + (\text{SIGMAI}*\text{PLENGI}*\text{RNGTER}(\text{I})*\text{DAZCLR}*\text{GTBELO}*\text{GRBELO}) \tag{3.13-10}$$

where	SIGMAI	=	clutter reflectivity value
	PLENGI	=	clutter patch length
	RNGTER(I)	=	range to i^{th} point in terrain profile from radar
	DAZCLR	=	azimuth increment for clutter computations
	GTBELO	=	normalized transmit antenna gain
	GRBELO	=	normalized receive antenna gain

6. Compute the measured multipath factor from the measured signal data as:

$$F_m = \text{Measured signal} - 10\log_{10}(\text{RCS}_{cr} + \text{CLTRCS}) \tag{3.13-11}$$

7. Run modified ALARM and record the multipath factor at each range increment. Visually compare measured and ALARM multipath factor vs range plots.

8. Statistically compare the differences in measured and modeled multipath factors by computing the mean difference and standard deviation of the differences.

9. Modify ALARM to accept measured multipath propagation loss as an input, bypassing the model calculation of multipath propagation.

10. Run the multipath-modified ALARM and unmodified ALARM, decreasing the target RCS until initial detection occurs within the flight path. This is necessary because use of the Eglin AFB test RCS always results in target detection, beyond the portion of the flight path of interest for validating ALARM.

11. Statistically compare differences in target detection range output by the multipath-modified and unmodified versions of ALARM.

Results and Interpretation: The measured flight profiles for both the nominal 10 meter and 20 meter flight paths are shown in figures 3.13-2 and 3.13-3, respectively. The measured target altitude is plotted versus the target slant range from the radar over the range of measurement (approximately 2 km to 13 km). Although the flight profile is intended to be at a constant altitude, the measured altitude (± 3.0 meter accuracy) appears to fluctuate significantly. As shown by the multipath sensitivity analysis, as documented in ASP II, the multipath propagation loss is sensitive to altitude differences as small as one meter.

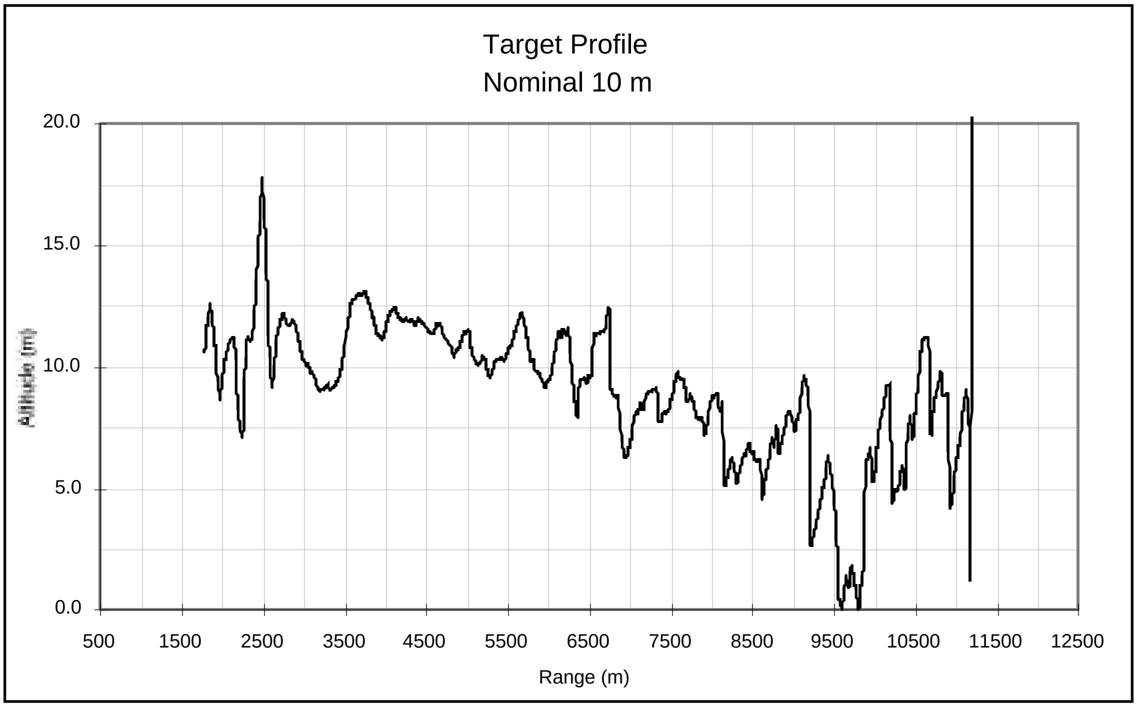

Figure 3.13-2 10 m Flight Path

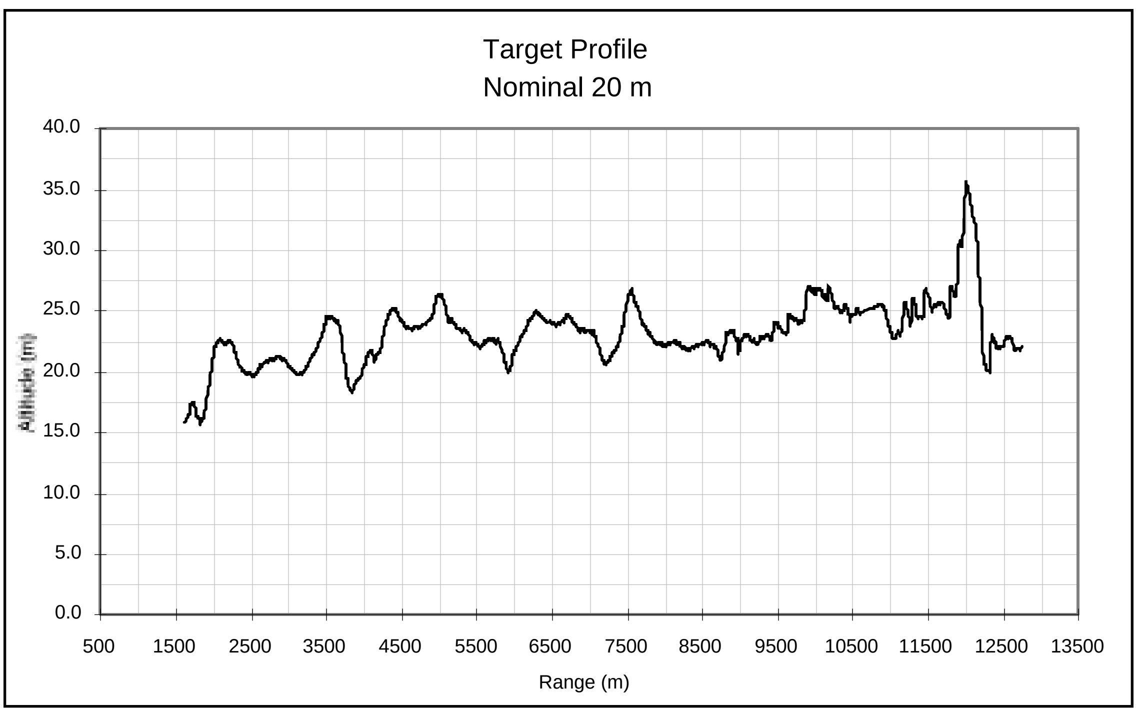

Figure 3.13-3 20 m Flight Path

Figures 3.13-4 and 3.13-5 are plots of the measured multipath propagation loss versus target range for the nominal target altitudes of 10 meters and 20 meters, respectively. The measured data as shown have been adjusted first by removing the target RCS, shown as the "no clutter" plot, and then further adjusted by removing the predicted equivalent clutter signal RCS. As can be observed, the clutter signal has a minimal contribution to the composite propagation loss.

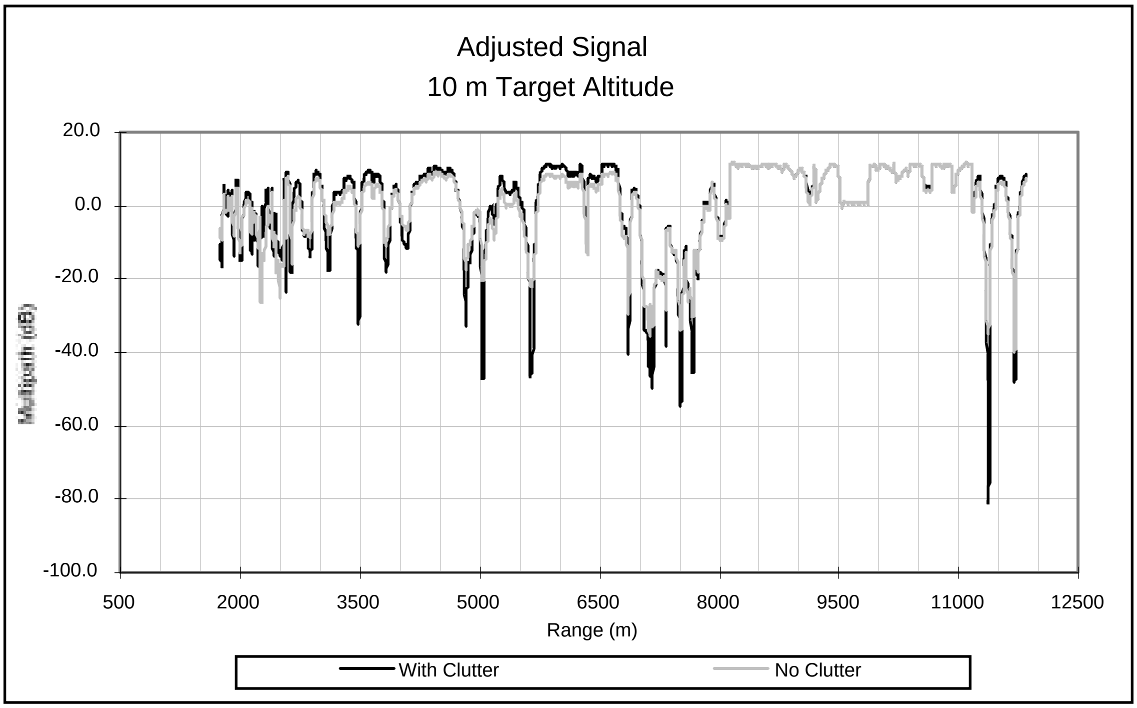

Figure 3.13-4 Clutter Impact on Measured Multipath, 10 m Target Altitude

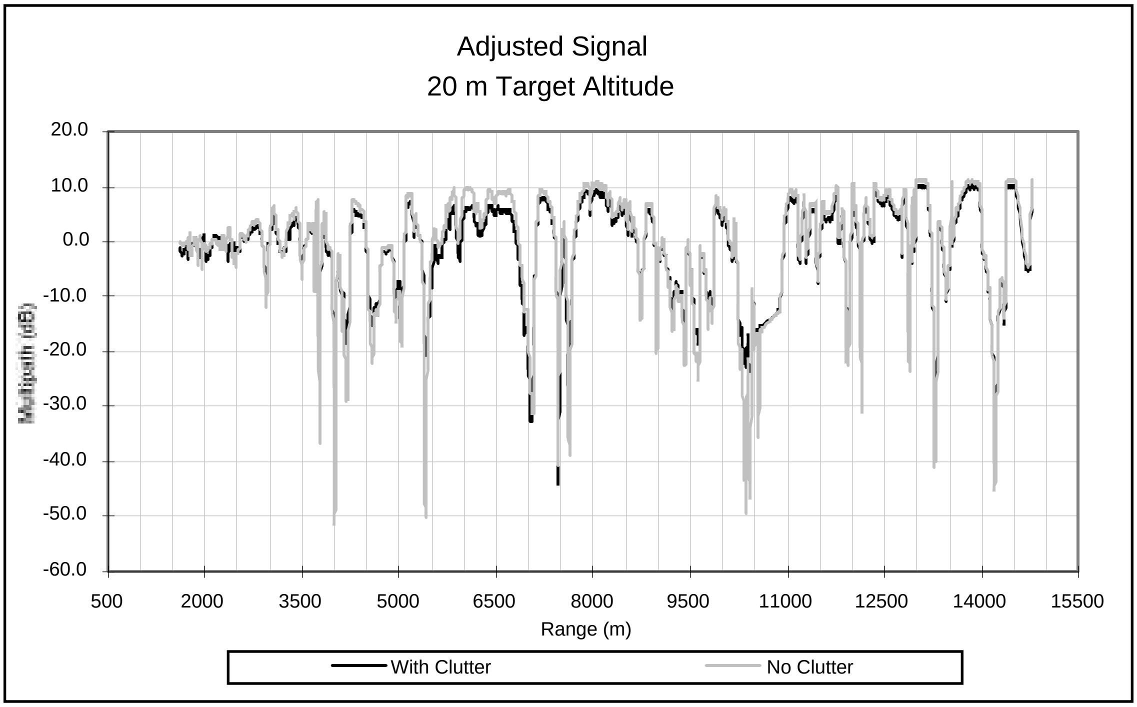

Figure 3.13-5 Clutter Impact on Measured Multipath, 20 m Target Altitude

Finally, figures 3.13-6 and 3.13-7 are comparative plots of measured and ALARM-predicted multipath loss versus range to the target for nominal target altitudes of 10 meters and 20 meters, respectively. At a target altitude of 10 meters, there appears to be some correlation of measured versus modeled multipath propagation losses while there is little apparent correlation at 20 meters flight altitude.

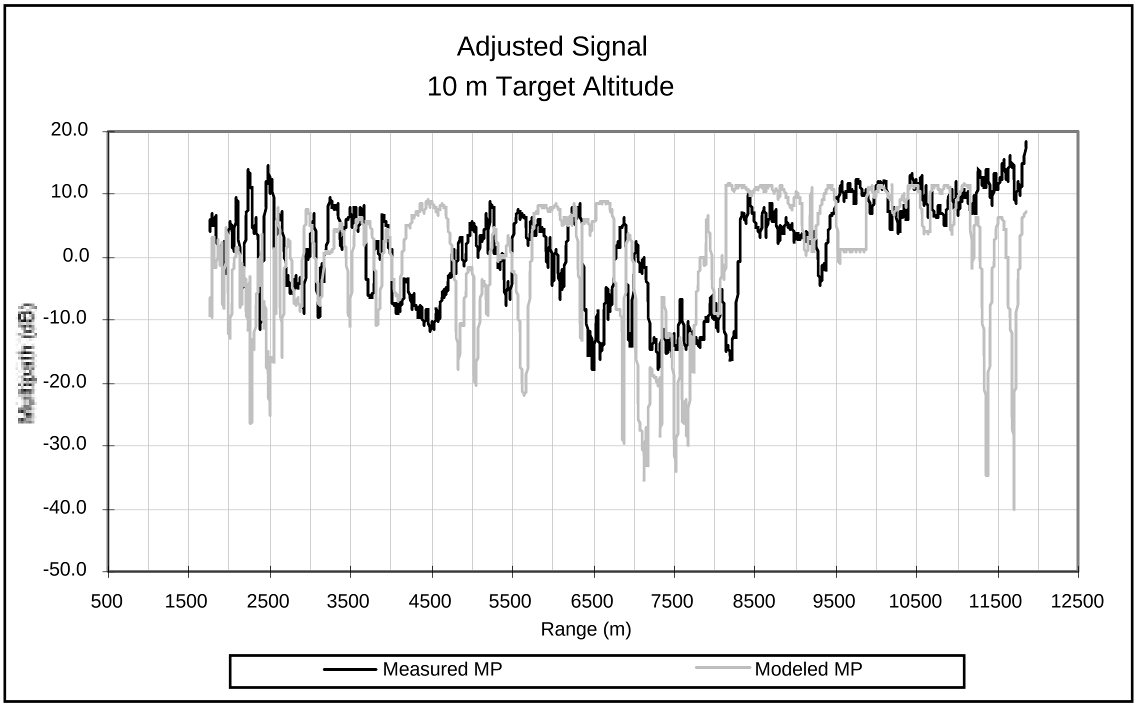

Figure 3.13-6 Measured vs. Modeled Multipath, 10 m Target Altitude

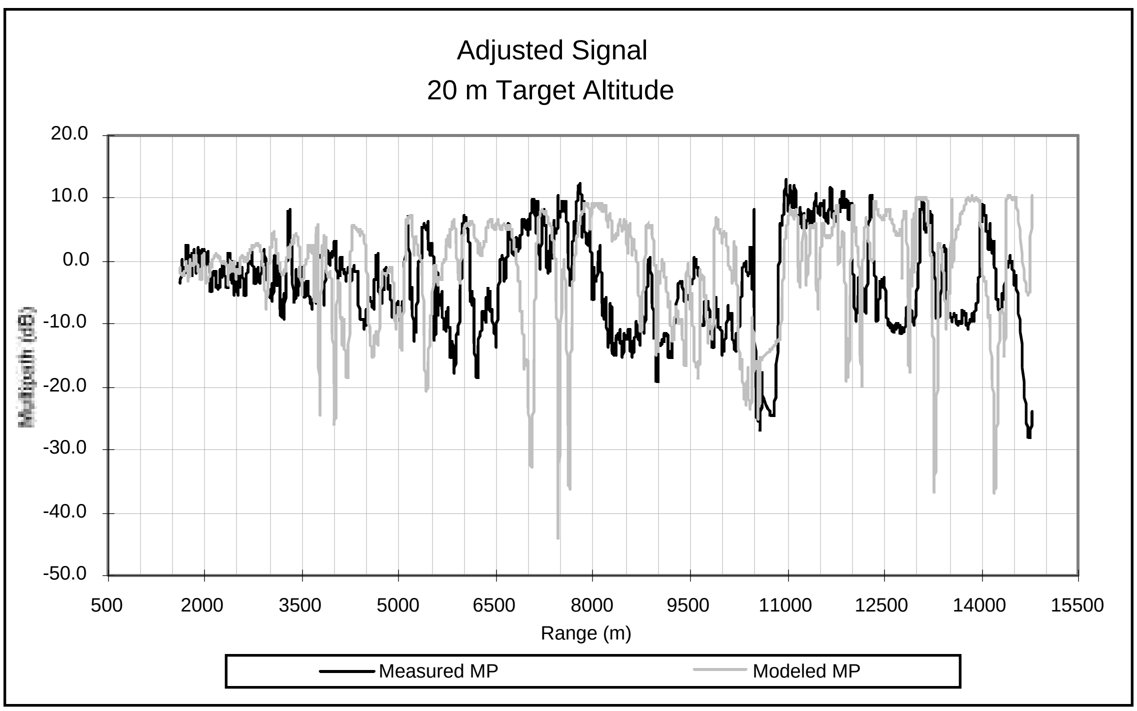

Figure 3.13-7 Measured vs. Modeled Multipath, 20 m Target Altitude

In order to quantify the variance in measured and modeled multipath propagation, the mean difference and standard deviation from the mean difference in multipath propagation were calculated; the results are shown in table 3.13-1. For the 10 meter target altitude, the mean difference between measured and modeled propagation loss is only 1.02 dB, while the standard deviation is 11.01 dB. Similarly, at 20 meters target altitude, the mean difference is -1.91 dB and the standard deviation is 11.49 dB. Although the mean difference in measured vs. modeled multipath propagation loss is small, the deviation from the mean is significant. It is believed that the large deviation from the mean difference in measured and predicted multipath propagation loss is attributed to the inaccuracy of the measured altitude (± 3 meters) relative to the required measurement accuracy of less than 1.0 meter, leading to an inconclusive determination of the validity of the modeled multipath functional element.

Table 3.13-1 Multipath Propagation Loss Variance

Case	Mean Difference (dB)	σ (dB)
10 m Target Altitude, Measured Loss	1.02	11.81
10 m Target Altitude, Modeled Loss		
20 m Target Altitude, Measured Loss	-1.91	11.49
20 m Target Altitude, Modeled Loss		

Conclusions: The validity assessment of the multipath propagation functional element as modeled in ALARM is inconclusive. Although the Eglin AFB test was superbly conducted, sensitivity analysis shows that the measured multipath propagation losses could not be replicated by the modeled multipath function considering the achievable accuracy of the target altitude measurements.

3.13.2 National Telecommunications and Information Administration (NTIA) One-Way Pattern-Propagation Tests

Validation Objective: The objective of the validation test is to compare the measured and ALARM-modeled one-way pattern-propagtion factors and determine the impact of any differences on overall model operation.

Measures of Effectiveness: Because of the relationship between the maximum detection range of a radar and the pattern-propagation factor, a 10% relative difference between the measured and modeled detection ranges of a radar corresponds to roughly a 1.0 dB difference between the measured and modeled one-way pattern-propagation factors. Even if a 25% relative difference between measured and modeled detection ranges was acceptable, this would correspond to a 2.0 dB difference between measured and modeled one-way pattern-propagation factors. In either instance, differences this small will be extremely difficult to achieve. Therefore, no MOE was selected for this test.

Test Description: The one-way pattern-propagation factor data were obtained from the National Telecommunications and Information Administration (NTIA). Data from hundreds of sites were collected by NTIA over a period of years in Colorado, Idaho, Ohio, Virginia, Washington, and Wyoming.

Data Description: The test data consists of measured one-way pattern-propagation factors collected from hundreds of sites at frequencies of 230 MHz (VHF) , 410 MHz (UHF), 751 MHz (UHF), 910 MHz (UHF), 1846 MHz (L-Band), 4595 MHz (C-Band), and 9190 MHz (X-Band).

In addition to the one-way pattern-propagation factor, the NTIA data also includes the locations of the radar and target (receiver) to the nearest arc second in latitude and longitude, the heights above the terrain of the radar and target (receiver), the radar frequency, the radar antenna polarization, and the terrain conductivity. The antenna gain, the terrain dielectric constant, and the refractivity factor were not provided.

Data Processing: The immediate availability of DMA DTED for the Colorado sites and terrain profiles of varying roughness influenced the decision to use the Colorado measured data to compare with the ALARM-modeled data.

The terrain profiles between the transmitters and receivers were classified according to the factor h, the standard deviation of the terrain heights, into the following categories:

Table 3.13-2 Categorization of Terrain Profiles by Height

Type of Terrain	Δh(m)	Number of Profiles
Very smooth plains	$\Delta h \leq 5$	7
Smooth plains	$5 < \Delta h \leq 20$	38
Slightly rolling plains	$20 < \Delta h \leq 40$	49
Rolling plains	$40 < \Delta h \leq 80$	53
Hills	$80 < \Delta h \leq 150$	13
Mountains	$150 < \Delta h \leq 300$	17
Rugged mountains	$300 < \Delta h \leq 700$	17
Extremely rugged mountains	$\Delta h > 700$	2
Total Number of Profiles: 196		

This table is reproduced from table 1, page 6 of ESSA TECHNICAL REPORT ERL 79-ITS 67, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain, A Computer Method-1968," by A.G. Longley and P.L. Rice [A.2-19]. A similar categorization is in figure 4.4, page 24 of *Radar Propagation at Low Altitudes*, by M.L. Meeks [A.2-20].

The NTIA package contained a retrieval program for searching the database and storing selected information in ASCII files. This program was used to retrieve all propagation data for sites located in Colorado. A FORTRAN program was written which created ALARM input files from the available data.

The inputs to ALARM which contribute to the computation of the pattern- propagation factor and their sources for the analysis are:

Table 3.13-3 Inputs to ALARM

Type of Input	Description of Input	Source
Radar	The radar latitude and longitude	NTIA
	The radar antenna height	NTIA
	The radar transmitted frequency	NTIA
	The radar antenna polarization	NTIA
	The radar antenna gain pattern	SAIC
Target	The target latitude and longitude	NTIA
	The target height	NTIA

Table 3.13-3 Inputs to ALARM

Type of Input	Description of Input	Source
Environment	Terrain profile between radar and target	DMA
	The terrain dielectric constant	SAIC
	The terrain conductivity	NTIA
	The terrain roughness factor	SAIC

As indicated, the radar antenna gain pattern was not supplied by NTIA. For these tests, the target (receiver) was generally at very low altitude above the terrain (usually 10-25 meters). Thus, the effective reflecting terrain was illuminated almost entirely by the main beam of the antenna. For this reason an isotropoic antenna pattern was assumed.

The terrain dielectic constant, the terrain roughness factor, and the atmospheric refractivity factor were also not supplied.

For frequencies ranging from UHF to X-Band and soil moisture contents ranging from 0.3% to 20%, the terrain dielectric constant varies from approximately 3 to 10. MIT's Lincoln Laboratory has used a value of 6.0 which is applicable over a wide range of frequencies for 10% soil moisture content. This was the value chosen for use in ALARM.

When an electromagnetic wave strikes a rough surface the amplitude of the reflected wave is reduced. The terrain roughness factor ranges in value from 0.0 (very rough surface) to 1.0 (very smooth surface) and is multiplied times the reflection coefficient for a perfectly flat and smooth surface. Various values of the terrain roughness factor were used in ALARM, depending on the radar frequency and the terrain profile.

To account for the bending of electromagnetic waves in the earth's atmosphere, the radius of the earth is multiplied by the refractivity factor. Curved ray paths are then considered to be straight. At altitudes less than 1 km the refractivity factor varies from approximately 1.25 to 1.45 over the United States, with 4/3 being a standard working value. In the absense of additional information, 4/3 was the value chosen for use in ALARM.

Analysis Procedures: The NTIA data contained the measured one-way pattern-propagation factor for each radar/receiver combination tested. To generate pattern-propagation factors in ALARM, the model was run with appropriate inputs for each of the radar/receiver combinations for which data existed in the NTIA data. ALARM computes F^4, the two-way pattern-propagation factor, for each receiver height above the terrain. The NTIA data contains F^2, the one-way pattern-propagation facor, for each receiver height. In decibels, F^2 translates to

$$F^2 \text{ (in dB)} = 10\log_{10}F^2 = 20\log_{10}F$$

ALARM models the pattern-propagation factor by specular reflection (multipath), diffraction, or a combination of both. Diffraction is computed by knife-edge diffraction, spherical-earth diffraction, or a combination of both. The guidelines for choosing these methods are illustrated in figure 3.13-1.

Results and Interpretation: This section first presents graphical comparisons of measured and modeled one-way pattern-propagation factors for one site for each of the eight terrain types. A summary of overall results is then presented.

Site 172 is located in an area designated as very smooth plains. The transmitting antenna is 6.6 meters above the terrain and the frequency is 230 MHz. The receiver is located at a ground range of 4.6 km and varies in altitude from one to 24 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-8. Although this terrain profile is categorized as very smooth plains, the receiver is masked from the transmitter until it is greater than three meters above the terrain. The method chosen by ALARM for computing the one-way pattern-propagation factor is spherical earth diffraction. A comparison between measured and modeled results is shown in figure 3.13-9. In general there is good agreement between results, with modeled results on average being slightly higher than measured results.

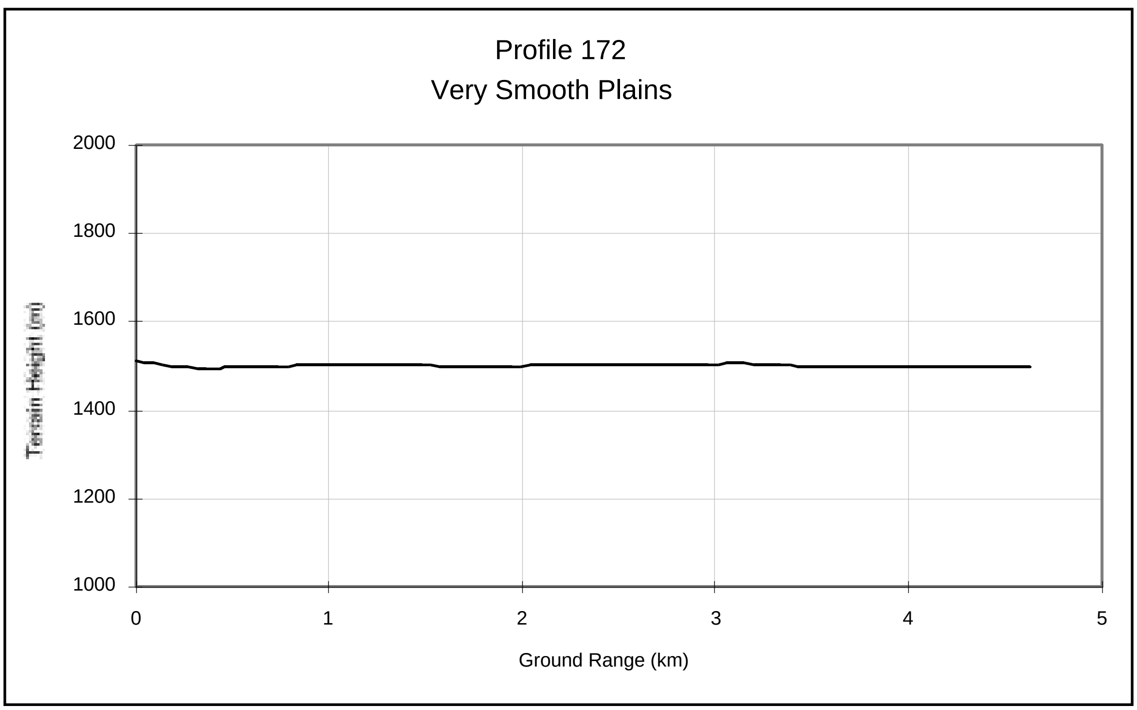

Figure 3.13-8 Profile 172 - Very Smooth Plains

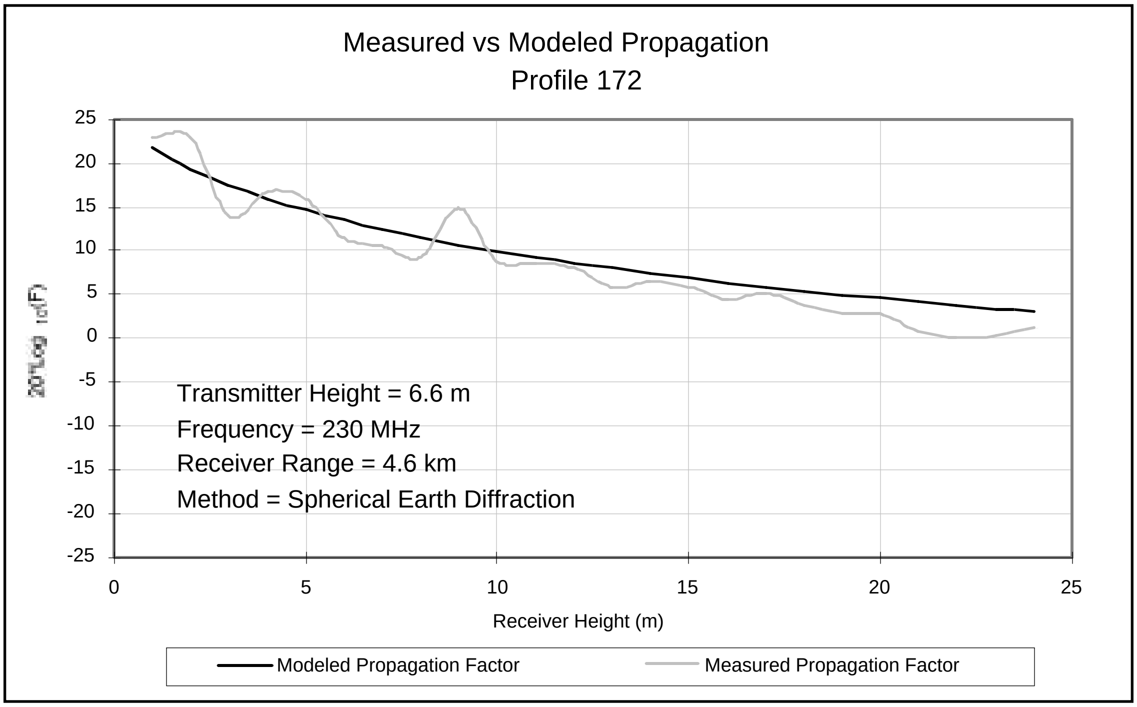

Figure 3.13-9 Measured vs Modeled Propagation, Profile 172

Site 34 is located in an area designated as smooth plains. The transmitting antenna is 7.3 meters above the terrain and the frequency is 4595 MHz. The receiver is located at a ground range of 19.7 km and varies in altitude from one to 13 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-10. A clear line-of-sight exists between the transmitter and receiver at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is specular reflection (multipath). A comparison between measured and modeled results is shown in figure 3.13-11. In general, there is fairly good agreement between results when the receiver is less than 10 meters in altitude, but some divergence at higher alitudes. The multipath method is very sensitive to the phases of the specularly reflected rays. The higher the frequency, the more oscillatory the behavior of the pattern-propagation factor becomes. Inaccuracies in the terrain elevation data can cause errors in the phase computation as well as in the amplitude of the specular reflections.

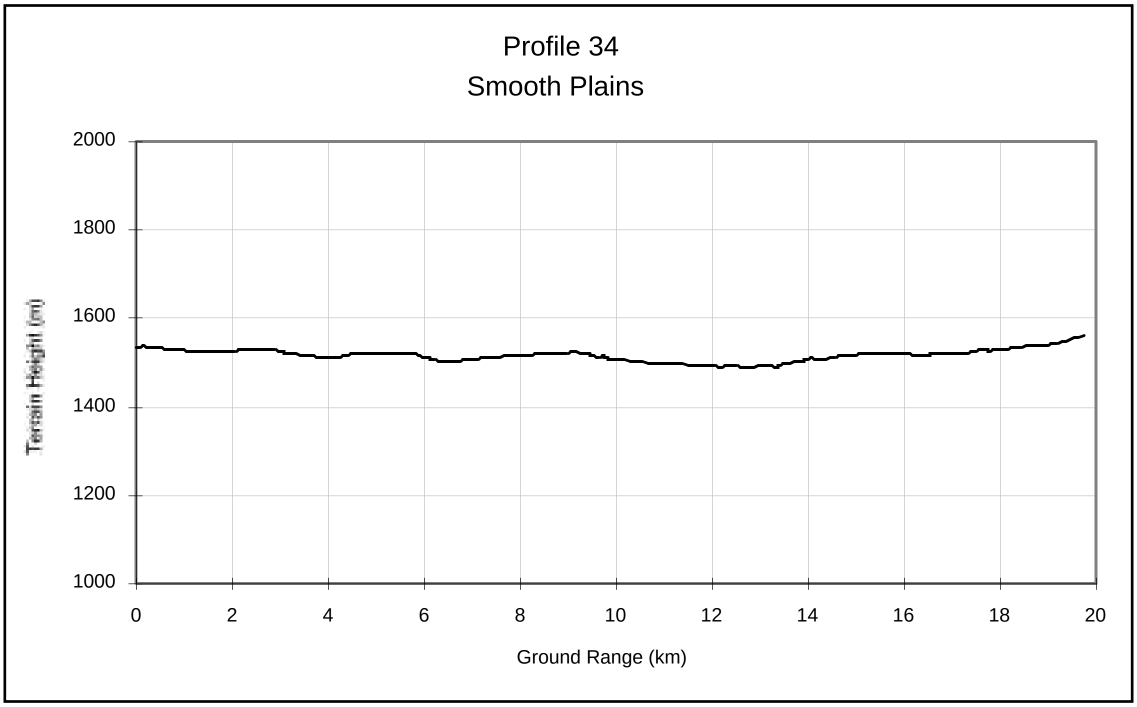

Figure 3.13-10 Profile 34 - Smooth Plains

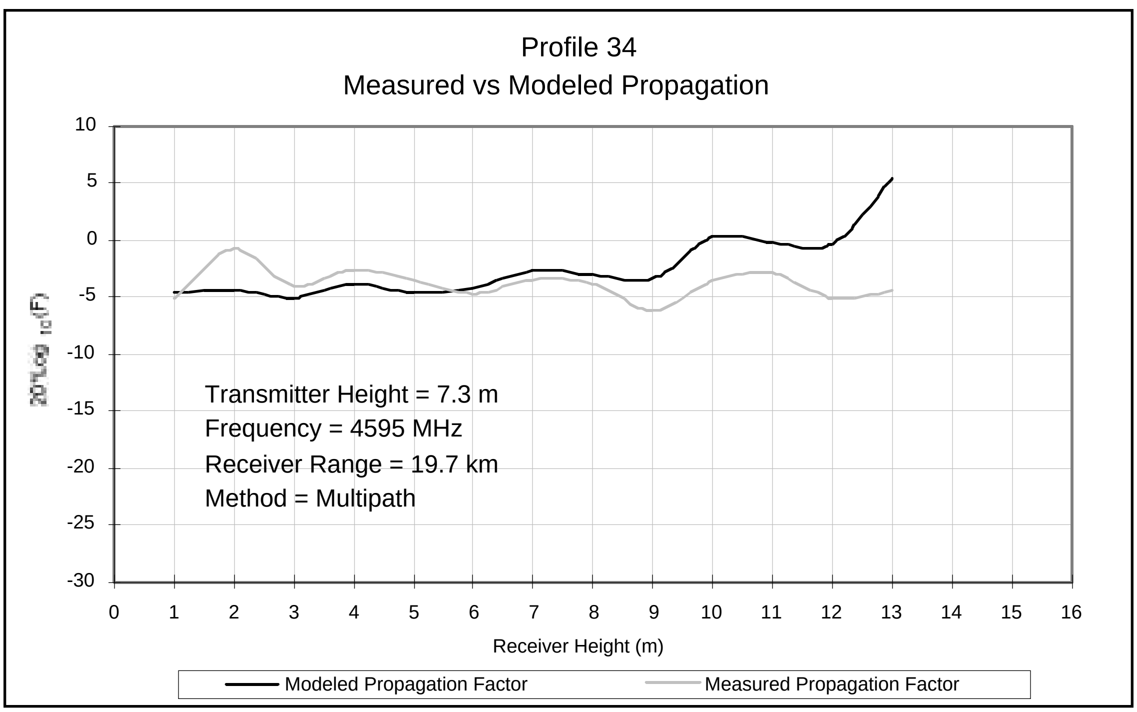

Figure 3.13-11 Measured vs Modeled Propagation, Profile 34

Site 129 is located in an area designated as slightly rolling plains. The transmitting antenna is 7.3 meters above the terrain and the frequency is 910 MHz. The receiver is located at a ground range of 19.4 km and varies in altitude from one to 15 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-12. The receiver is masked from the transmitter at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is spherical earth diffraction. A comparison between measured and modeled results is shown in figure 3.13-13. As the figure indicates, there is very poor correlation between the results, with modeled results being approximately 40-45 dB greater than measured results. These results should not be interpreted as a failure of the spherical earth diffraction method but as an instance in which the incorrect method was chosen. When the terrain type was slightly rolling plains or rolling plains, and ALARM chose spherical earth diffraction to determine the pattern-propagation factor, the results were uniformly disappointing. These may represent instances where knife-edge diffraction or a weighted average of spherical earth diffraction and knife-edge diffraction is more appropriate as the diffraction method; changes to the method selection algorithm implemented in ALARM are needed to accomplish this.

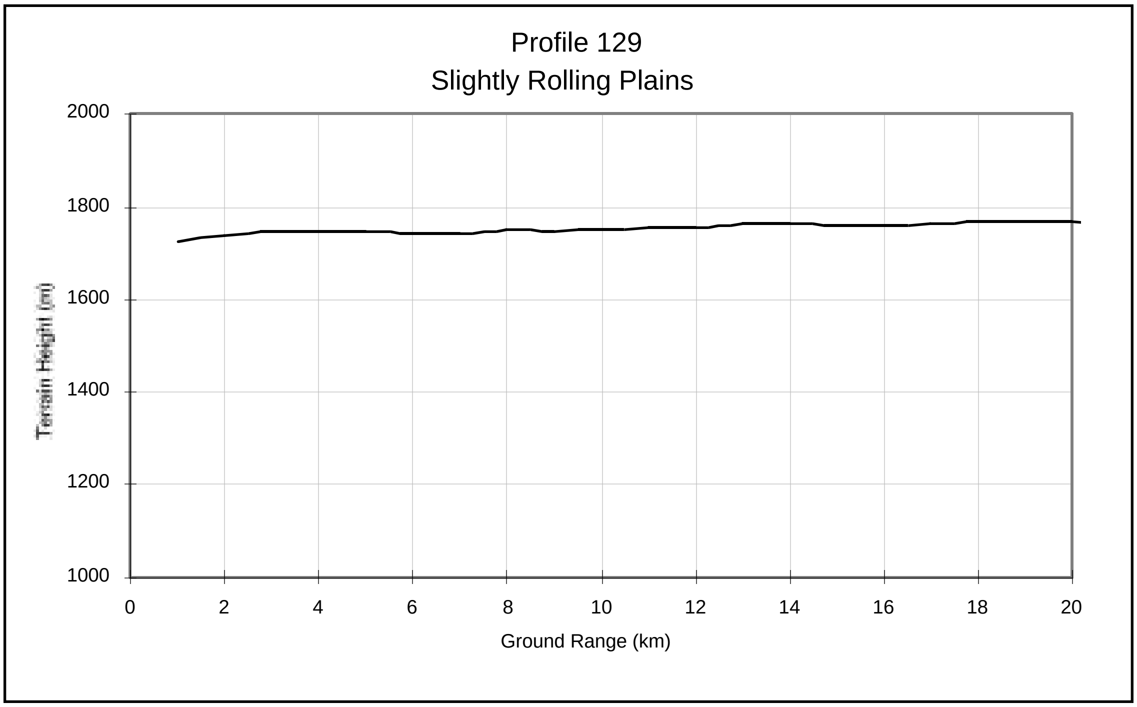

Figure 3.13-12 Profile 129 - Slightly Rolling Plains

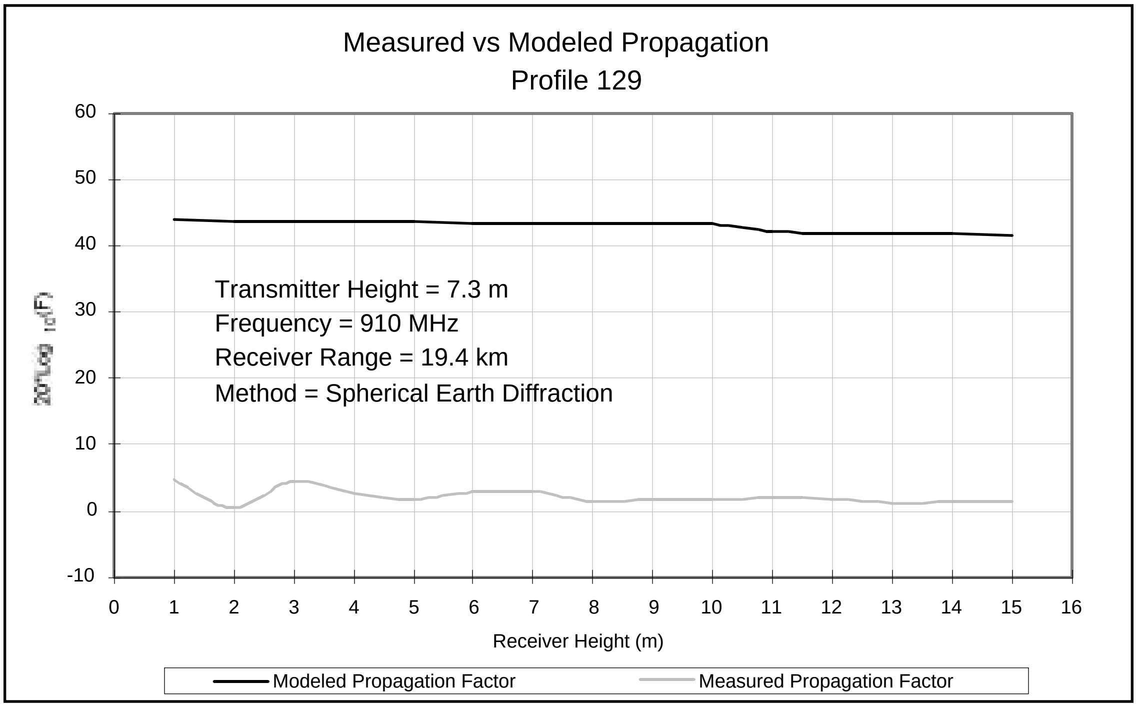

Figure 3.13-13 Measured vs Modeled Propagation - Profile 129

Site 149 is located in an area designated as rolling plains. The transmitting antenna is 6.6 meters above the terrain and the frequency is 230 MHz. The receiver is located at a ground range of 54.2 km and varies in altitude from one to 15 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-14. A clear line-of-sight exists between the transmitter and receiver at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is knife-edge diffraction. A comparison between measured and modeled results is shown in figure 3.13-15. In general there is good agreement between results, with modeled results on average being slightly lower than measured results. There is considerable divergence between measured and modeled results at a receiver altitude of one meter. This behavior was noted at many sites and occurred often at the lowest receiver altitudes. The reason for this behavior is not currently known.

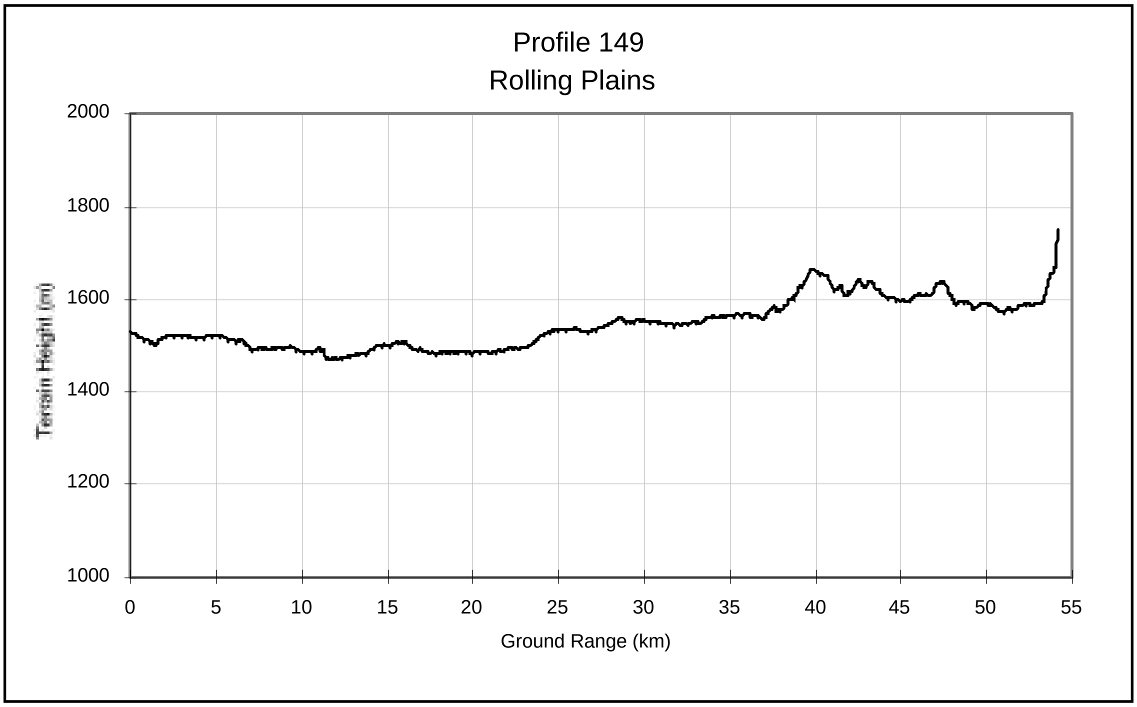

Figure 3.13-14 Profile 149 - Rolling Plains

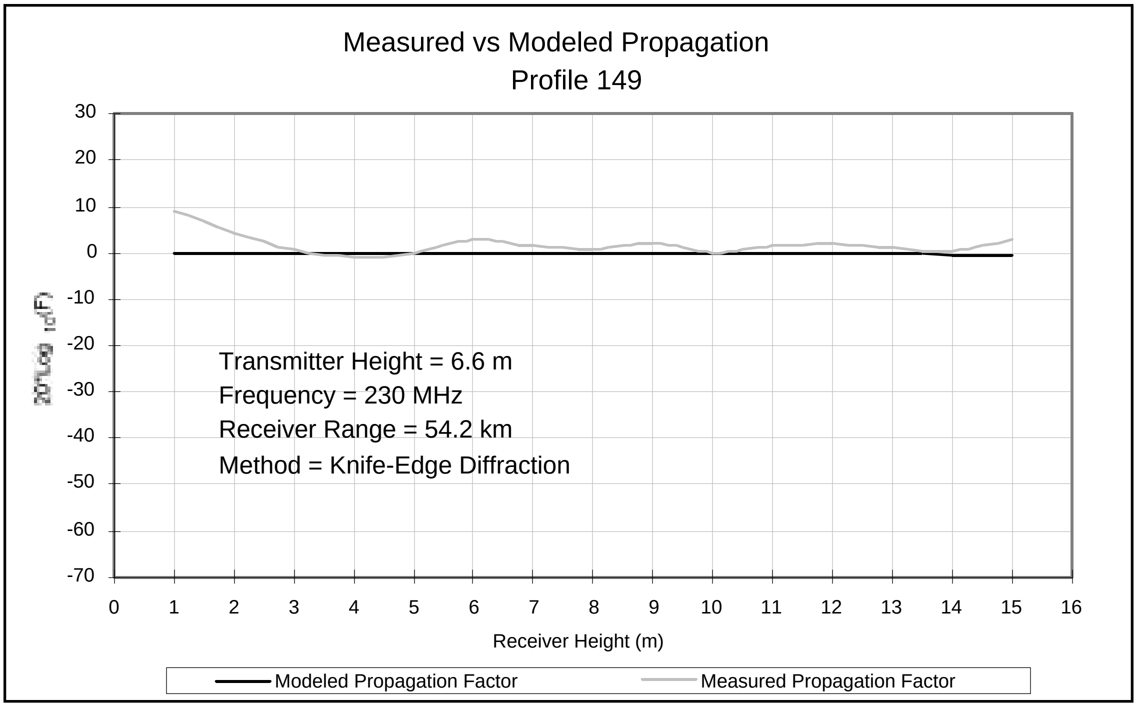

Figure 3.13-15 Measured vs Modeled Propagation - Profile 149

Site 56 is located in an area designated as hills. The transmitting antenna is 6.6 meters above the terrain and the frequency is 751 MHz. The receiver is located at a ground range of 97.3 km and varies in altitude from one to 13 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-16. The receiver is masked from the transmitter at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is a weighted average of knife-edge diffraction and spherical earth diffraction. A comparison between measured and modeled results is shown in figure 3.13-17. The oscillatory behavior of the measured results prevents this comparison from being described as good, but the low points of the oscillations are quite near the modeled results. In general, knife-edge diffraction and spherical earth diffraction produce results which are non-oscillatory in nature when the receiver is masked from the transmitter.

Figure 3.13-18 depicts the one-way pattern-propagation factor for a single knife-edge as a function of the normalized clearance. When the normalized clearance is greater than zero, a clear line-of-sight exists between the transmitter and receiver. If the normalized clearance is less than zero, the receiver is masked from the transmitter. When the receiver is masked, the behavior is non-oscillatory.

The normalized clearance is the ratio $\frac{\Delta}{\Delta_0}$ where Δ is the minimum clearance between the terrain profile and the line-of-sight between the radar and the target and Δ_0 is the Fresnel clearance. Δ and Δ_0 are depicted in figure 3.13-1.

Figure 3.13-19 depicts the one-way pattern-propagation factor for a single knife-edge on a flat plane as a function of the normalized clearance when specular reflection occurs on that portion of the plane between the knife-edge and the receiver. In contrast to figure 3.13-18, this function is oscillatory with decreasing amplitude as the receiver altitude increases. The portion of the site 56 terrain profile from approximately 60 km ground range to the receiver is a relatively flat inclined plane and may provide an area for specular reflection, which might explain the oscillatory results of figure 3.13-17. The current implementation in ALARM does not permit either reflection before diffraction or reflection after diffraction.

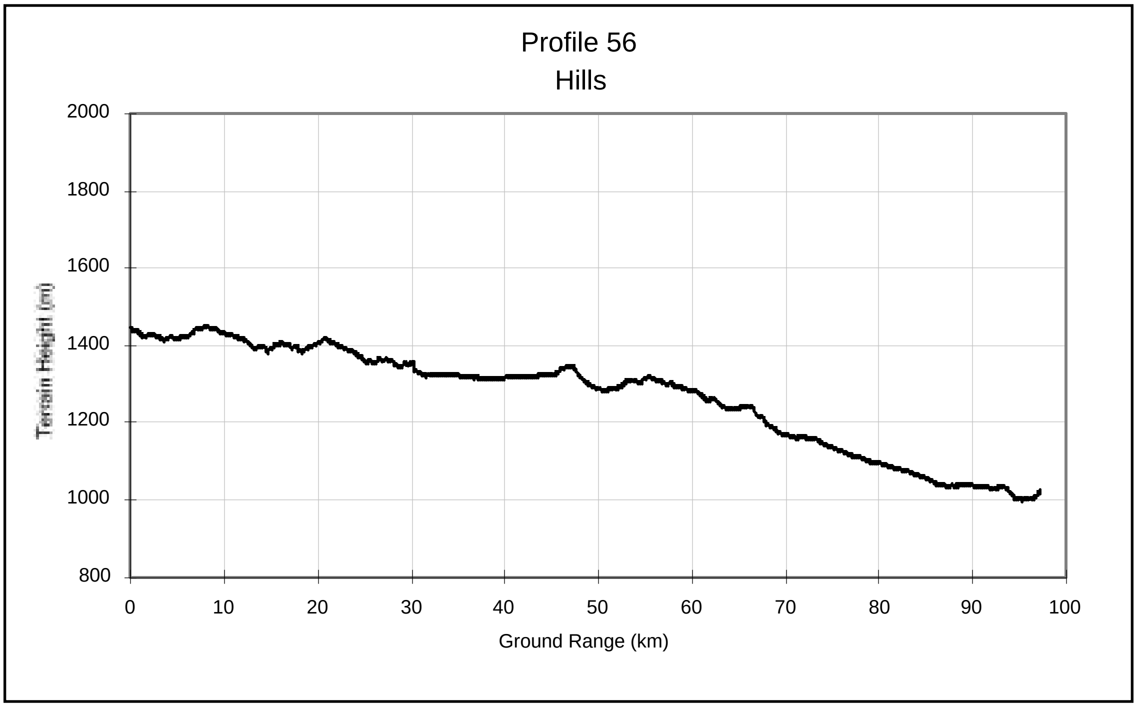

Figure 3.13-16 Profile 56 - Hills

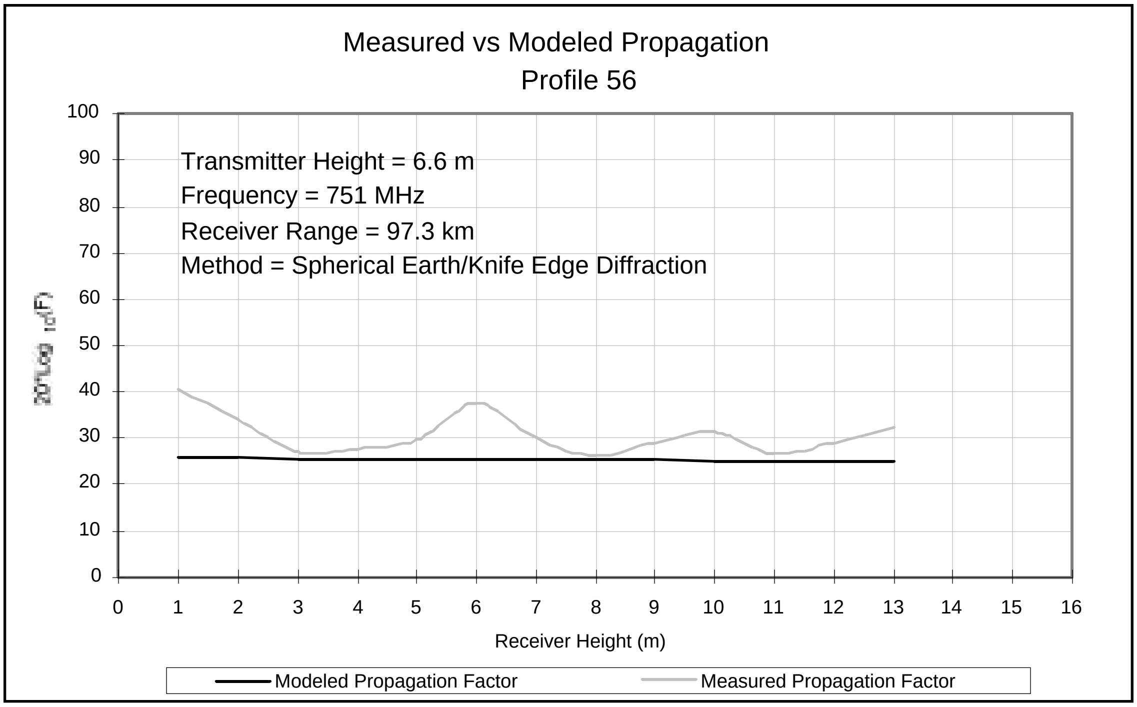

Figure 3.13-17 Measured vs Modeled Propagation - Profile 56

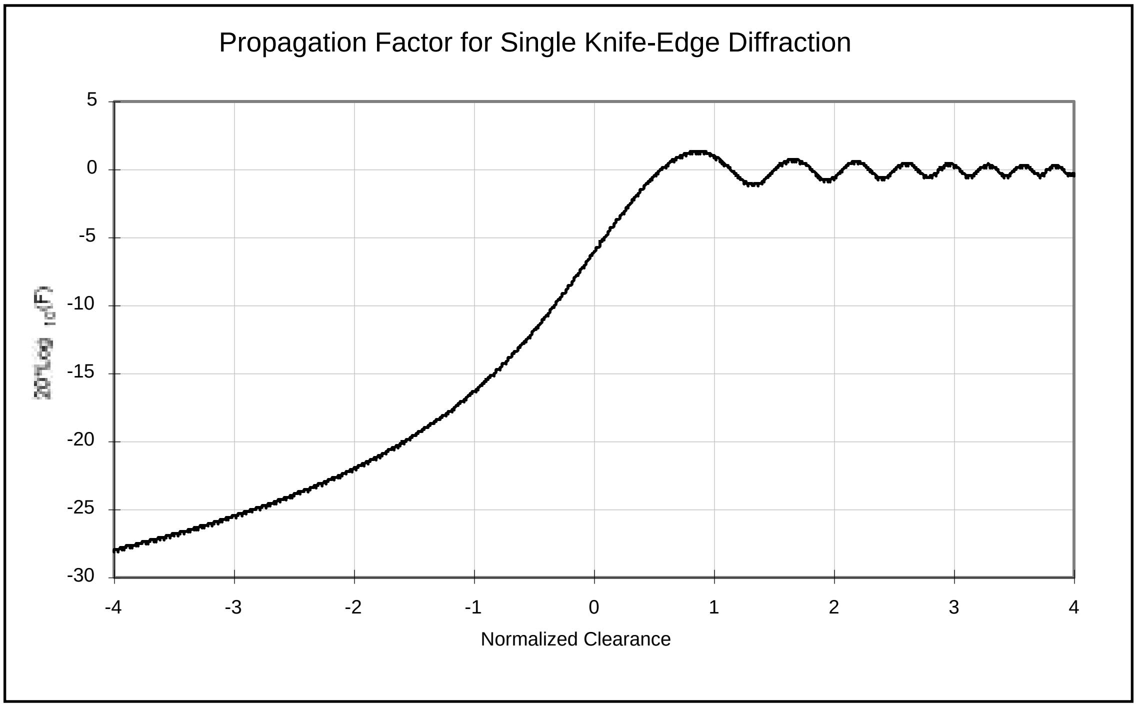

Figure 3.13-18 Propagation Factor for Single Knife-Edge Diffraction

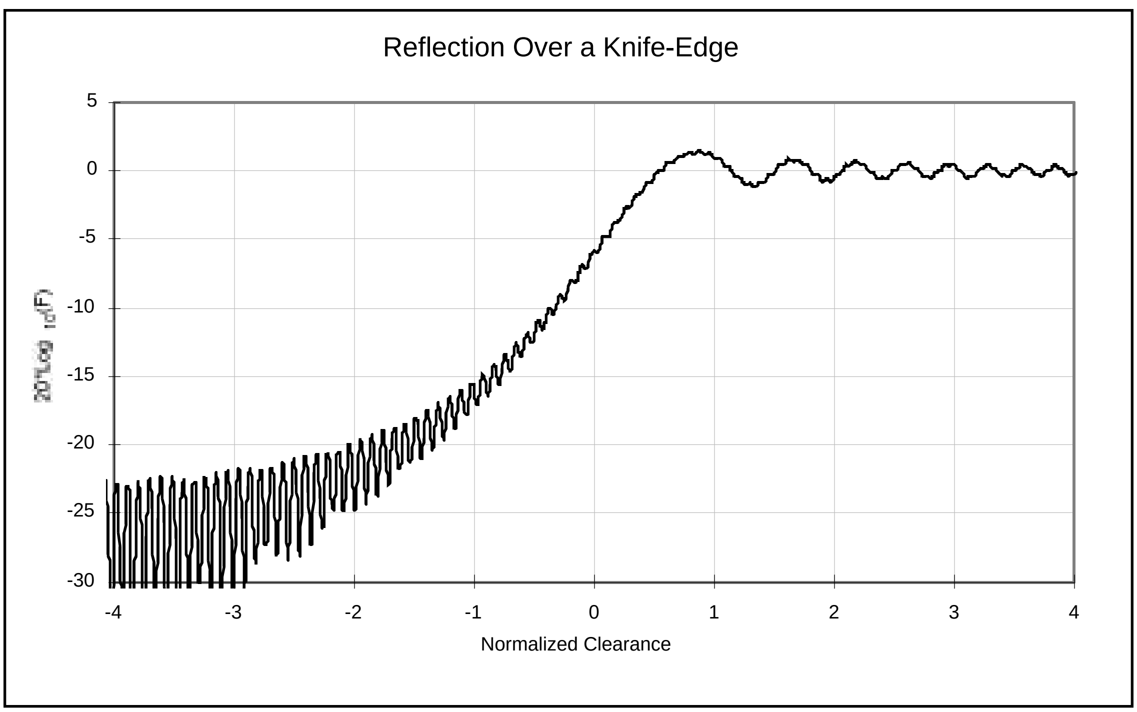

Figure 3.13-19 Reflection Over a Knife Edge

Site 38 is located in an area designated as mountains. The transmitting antenna is 7.3 meters above the terrain and the frequency is 9190 MHz. The receiver is located at a ground range of 20.5 km and varies in altitude from one to 13 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-20. A clear line-of-sight exists between the transmitter and receiver at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is specular reflection (multipath). A comparison between measured and modeled results is shown in figure 3.13-21. The results are mixed, with good agreement for receiver altitudes between three and six meters, and fair to poor agreement at other receiver altitudes. As stated earlier, the multipath method is sensitive to the phases of the specularly reflected rays. The higher the frequency, the more oscillatory the behavior of the pattern-propagation factor becomes. This terrain profile is relatively rugged from the transmitter to approximately 10 km ground range with several vertical obstacles, evident in figure 3.13-20. The influence of these obstacles (not related to specular reflections) will not be predicted by the model since multipath was the chosen method. Terrain elevation data inaccuracies can also cause errors in the phase computation as well as in the amplitude of the specular reflections.

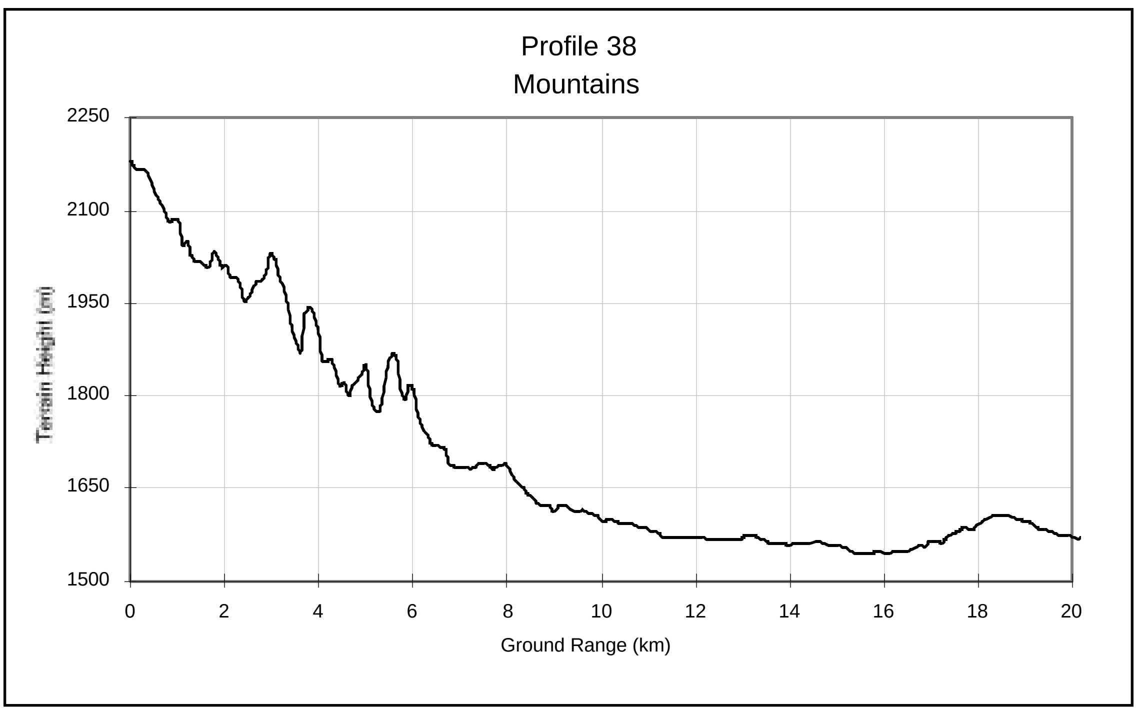

Figure 3.13-20 Profile 38 - Mountains

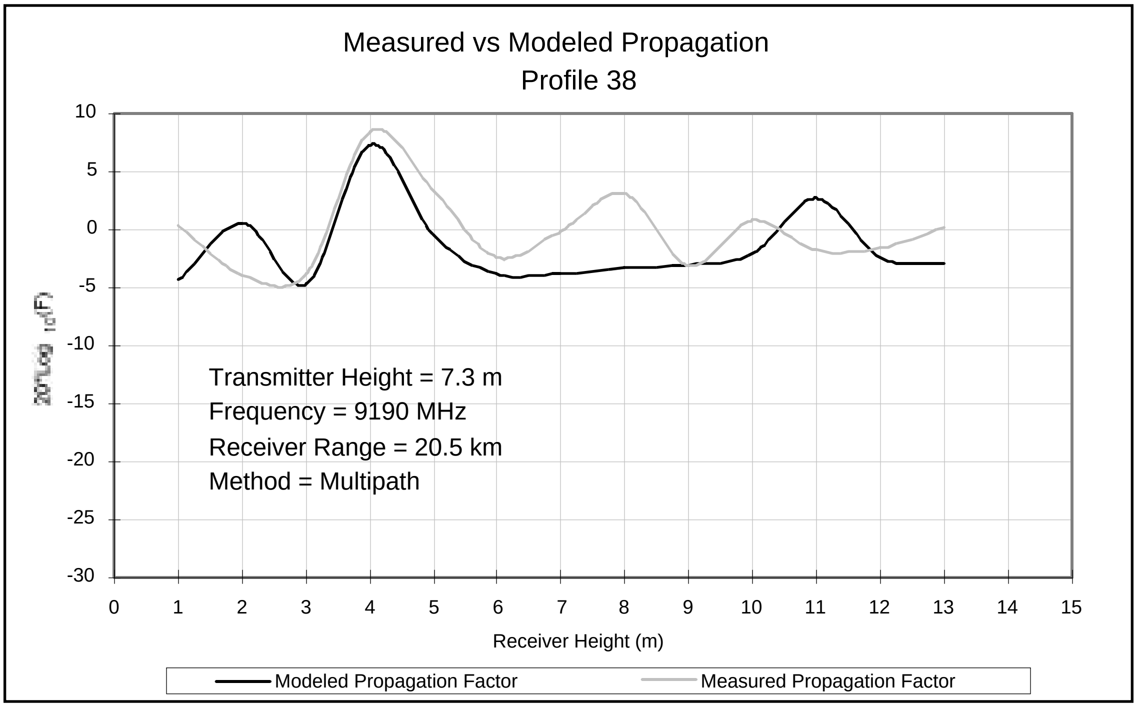

Figure 3.13-21 Measured vs Modeled Propagation - Profile 38

Site 49 is located in an area designated as rugged mountains. The transmitting antenna is 7.3 meters above the terrain and the frequency is 1846 MHz. The receiver is located at a ground range of 52.5 km and varies in altitude from one to 13 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-22. The receiver is masked from the transmitter at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is knife-edge diffraction. A comparison between measured and modeled results is shown in figure 3.13-23. The results are quite good for receiver altitudes between one and nine meters, with some divergence at higher receiver altitudes. Again, some oscillatory behavior is noted similar to that at site 56. This terrain profile also exhibits a relatively flat region beginning at approximately 40 km ground range and extending to the receiver. Specular reflection from this region, after knife-edge diffraction from several obstacles in the earlier portion of the profile, may contribute to this oscillatory behavior. ALARM is not currently capable of capturing these interactions.

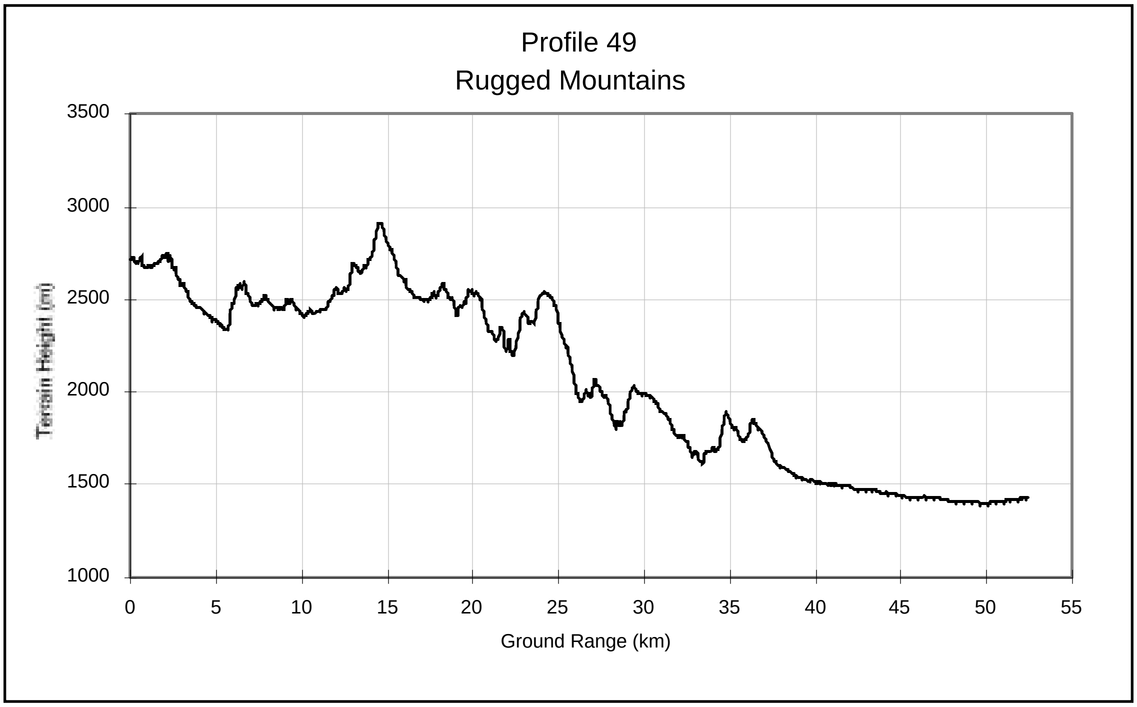

Figure 3.13-22 Profile 49 - Rugged Mountains

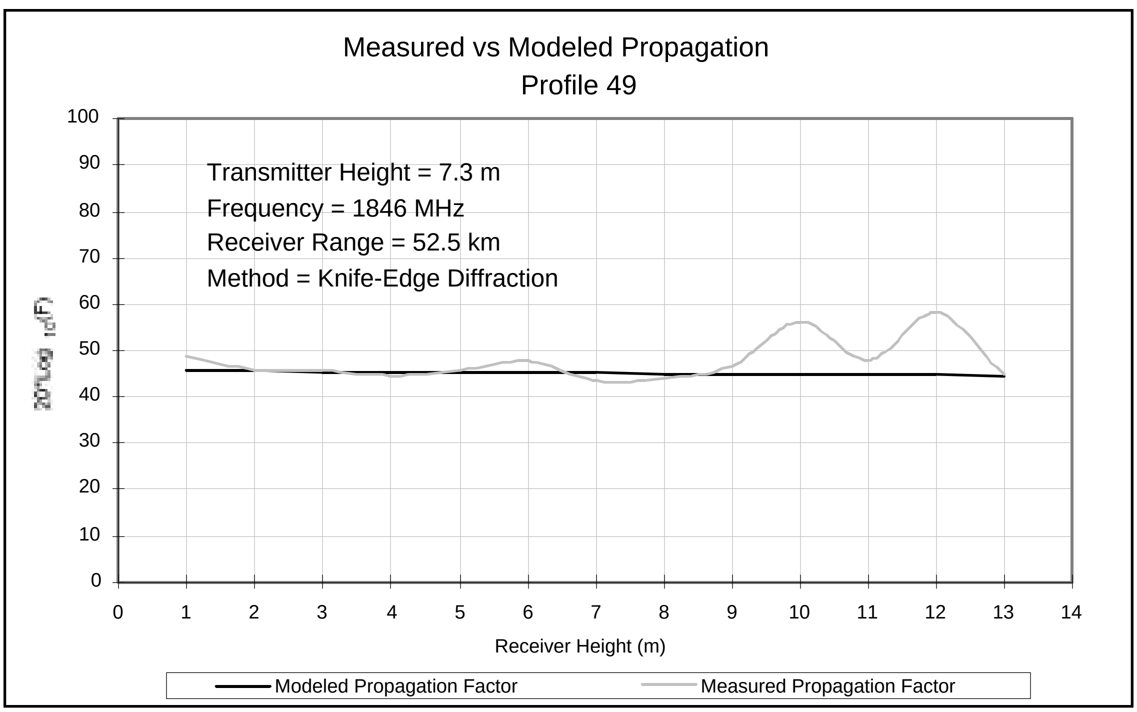

Figure 3.13-23 Measured vs Modeled Propagation - Profile 49

Site 60 is located in an area designated as extremely rugged mountains. The transmitting antenna is 6.6 meters above the terrain and the frequency is 410 MHz. The receiver is located at a ground range of 119.6 km and varies in altitude from one to 13 meters above the terrain. The terrain profile between the transmitter and receiver is shown in figure 3.13-24. The receiver is masked from the transmitter at each receiver altitude. The method chosen by ALARM for computing the one-way pattern-propagation factor is knife-edge diffraction. A comparison between measured and modeled results is shown in figure 3.13-25. Although the measured results are oscillatory in nature, the comparison with modeled results is fairy good except for a receiver altitude of 11 meters. A comparison of the measured result at this point with surrounding values suggests a possible outlier or at least a slightly larger measured value than might be expected. In either case, as has been mentioned several times previously, this type of oscillatory behavior is not currently captured in ALARM by pure knife-edge diffraction. Specular reflection either before or after diffraction by a knife-edge is necessary to capture this behavior.

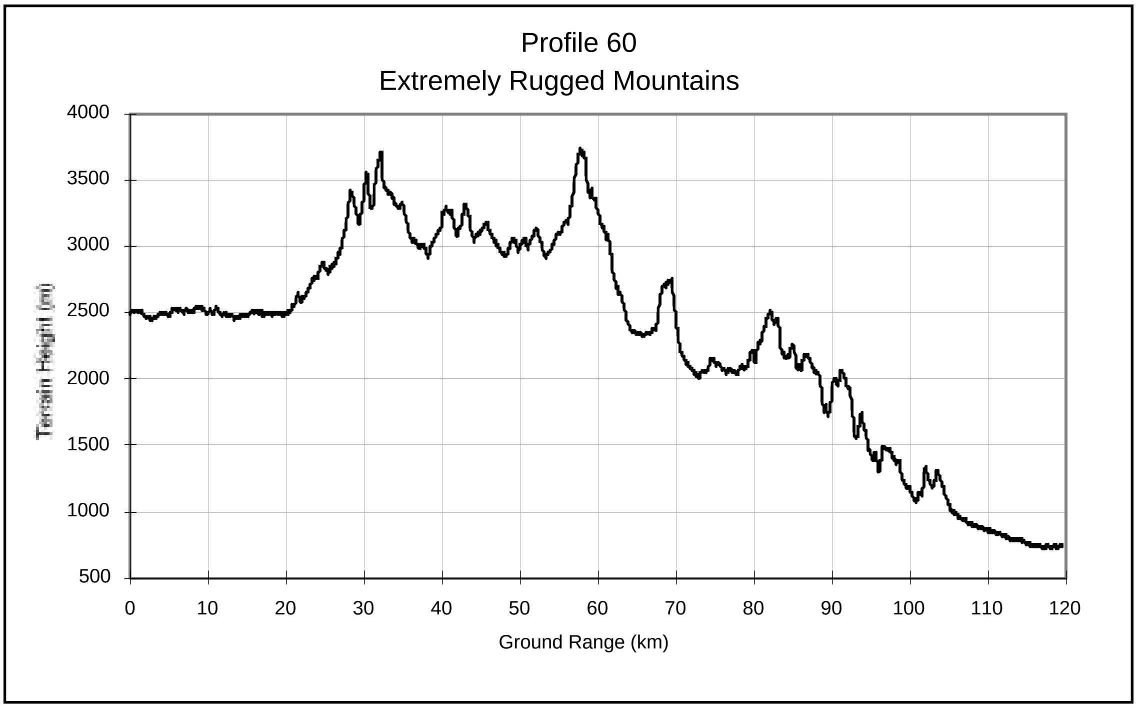

Figure 3.13-24 Profile 60 - Extremely Rugged Mountains

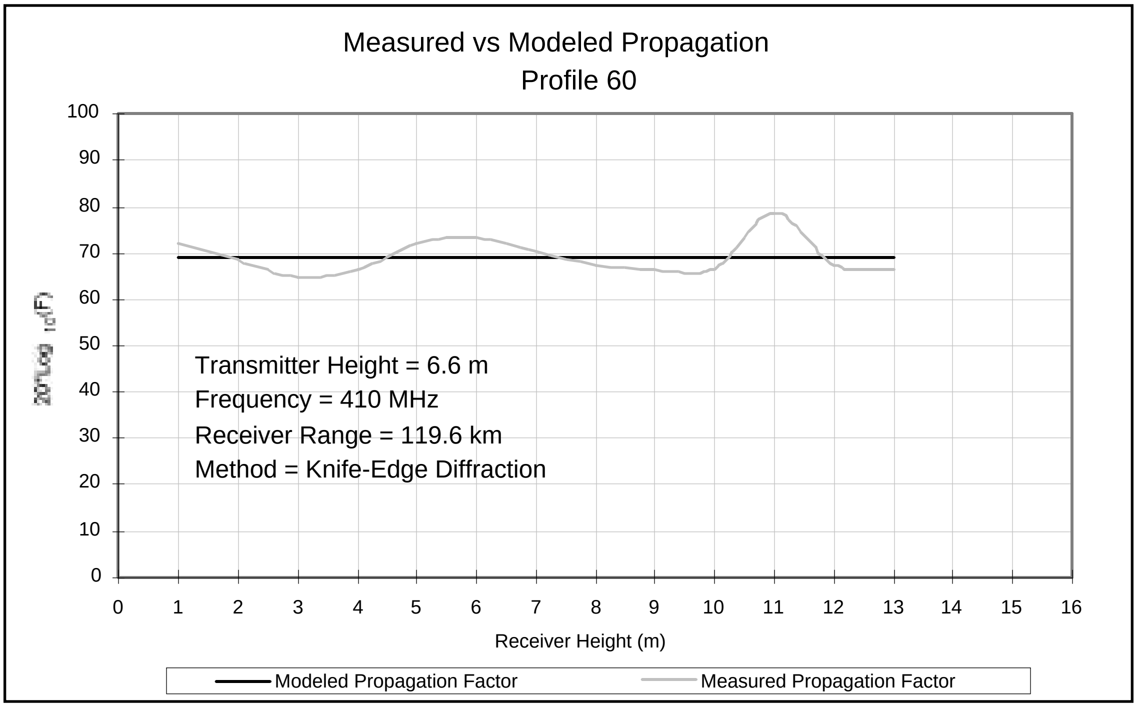

Figure 3.13-25 Measured vs Modeled Propagation - Profile 60

Table 3.13-4 presents the average differences between measured and modeled pattern-propagation factors as a function of terrain type and frequency over all sites for which data were available, when specular reflection (multipath) was the method selected by ALARM. Positive (negative) values indicate the modeled values were greater (less) than the measured values. With one exception, all table entries indicate that when multipath is the selected method, ALARM underestimates the pattern-propagation factor. Although not uniformly true, there is a trend toward larger differences as the frequency increases.

Table 3.13-4 Multipath Performance, Average Differences Between Measured and Modeled Results (dB)

Terrain Type	Frequency (MHz)						
	230.0	**410.0**	**751.0**	**910.0**	**1846.0**	**4595.0**	**9190.0**
Very smooth plains	-2.9793	-8.4924	6.2512	-7.4751	-14.1120	-19.6671	-23.3335
Smooth plains	-0.7605	-3.1656	-2.0922	-3.2136	-8.0115	-12.8565	-15.0812
Slightly rolling plains	-9.3756	-6.0142	-3.1711	-4.9530	-3.0131	-8.6011	-8.9204
Rolling plains	-5.0237	-4.0192	-3.9498	-5.8044	-4.5464	-4.3698	-4.7157
Hills	-	-	-1.7364	-	-6.5629	-14.1532	-19.1453
Mountains	-	-9.8529	-9.9911	-7.7180	-14.8248	-16.9908	-18.4265
Rugged mountains	-	-	-	-	-	-	-
Extremely rugged mountains	-	-	-	-	-	-	-

The phase difference corresponding to the path length difference at a specular point is given by

$$\varphi = \frac{2\pi\Delta R}{\lambda} \tag{3.13-12}$$

where φ = is the phase difference
ΔR = is the path length difference between the direct and specularly reflected rays
λ = is the radar wavelength.

As the frequency increases, or conversely, the wavelength decreases, a graphical depiction of the pattern-propagation factor will display an ever increasing number of peaks and nulls. In a point-to-point comparison, the modeled results may not match well with measured results although the general trend (peaks and nulls) is captured well. Terrain elevation inaccuracies can cause errors in the computed specular phase as well as in the amplitude of the specular reflections. A constant correction factor to the reflection coefficient to account for terrain roughness may also cause some of the differences. The reflection factor is given in ALARM by

$$\rho = \rho_s \rho_0$$

where ρ_0 is the round smooth earth reflection coefficient and ρ_s, $0 \le \rho_s \le 1$, is the correction factor (scattering coefficient) to account for the roughness of the terrain. For very rough terain, ρ_s is near zero and for very smooth terrain, ρ_s is near one. ALARM allows only a constant ρ_s value over all profiles when in fact ρ_s may be different for different profiles or may vary over a single profile.

Table 3.13-5 presents the average differences between measured and modeled pattern-propagation factors as a function of terrain type and frequency over all sites for which data were available, when knife-edge diffraction was the method selected by ALARM. Positive (negative) values indicate the modeled values were greater (less) than the measured values. All table entries indicate that when knife-edge diffraction is the selected method, ALARM underestimates the pattern-propagation factor. Intuitively, it seems inappropriate for knife-edge diffraction to be used to determine the pattern-propagation factor in areas designated as very smooth plains since this would seem to indicate a scarcity of ridges which could qualify as knife-edges. Nevertheless, as the first row of table 3.13-5 indicates, this method was used, with very poor results, in areas designated as very smooth plains. An improvement in the method selection algorithm is needed to prevent the selection of knife-edge diffraction in this situation. Spherical earth diffraction is probably more appropriate.

There seems to be no definite trend in differences as a function of frequency. A modified form of Deygout's method is used to determine the pattern-propagation factor due to multiple knife-edges. Although the method, as implemented in ALARM, may consider up to three knife-edges, MIT's Lincoln Laboratory has achieved good results with two knife-edges and that is the number currently considered by ALARM. A version of Deygout's method has been used over paths with up to five diffracting masks, and consideration of additional masks might bring modeled results into better agreement with measured results, especially in mountainous areas such as many of those considered in this report. As mentioned earlier, ALARM does not consider the effect of specular reflections on either side of the diffracting mask(s) to the knife-edge diffraction solution. This may also contribute to the observed differences.

Table 3.13-5 Knife-Edge Diffraction Performance,
Average Differences Between Measured and Modeled Results (dB)

Terrain Type	Frequency (MHz)						
	230.0	410.0	751.0	910.0	1846.0	4595.0	9190.0
Very smooth plains	-	-	-	-	-	-34.2908	-39.1332
Smooth plains	-13.4836	-11.6433	-13.2410	-12.3258	-18.5414	-22.1513	-23.8687
Slightly rolling plains	-9.1542	-9.6758	-10.3960	-13.4740	-17.6158	-19.3904	-19.0005
Rolling plains	-6.0016	-8.1870	-4.5520	-8.9247	-10.9875	-14.0548	-9.9580
Hills	-9.2557	-8.3061	-0.8600	-7.4082	-13.9973	-17.4502	-13.3163
Mountains	-16.3187	-14.6391	-15.7061	-20.9116	-21.3311	-24.7868	-22.4265
Rugged mountains	-3.8149	-6.3930	-2.4632	-8.4598	-11.6855	-13.6831	-5.3374
Extremely rugged mountains	-22.6912	-13.3508	-	-	-	-	-

Table 3.13-6 presents the average differences between measured and modeled pattern-propagation factors as a function of terrain type and frequency over all sites for which data were available, when spherical earth diffraction was the method selected by ALARM. Positive (negative) values indicate the modeled values were greater (less) than the measured values. Although not uniformly true, there is a trend toward larger differences as the frequency increases. Although many of the differences tend to be somewhat large, the terrain types indicated by slightly rolling plains, rolling plains, and mountains are by far the worst, with the mountain terrain modeled results being 45 dB less than the measured results. Slightly rolling plains and rolling plains results are also quite poor. As mentioned previously in regard to site 129, these terrain types should perhaps be handled by knife-edge diffraction or a weighted average of spherical earth diffraction and knife-edge diffraction rather than spherical earth diffraction alone. If this is the case, then mountain terrain results should also be determined in a similar manner. An improvement in the method selection algorithm is needed to prevent the selection of spherical earth diffraction alone in these situations.

Table 3.13-6 Spherical Earth Diffraction Performance,
Average Differences Between Measured and Modeled Results (dB)

Terrain Type	Frequency (MHz)						
	230.0	410.0	751.0	910.0	1846.0	4595.0	9190.0
Very smooth plains	3.9710	-1.9994	-	-10.7565	-12.1558	-8.0053	14.1645
Smooth plains	6.2150	-3.7010	-3.3345	-12.8489	-20.1685	-	-
Slightly rolling plains	5.9497	39.3042	40.0979	36.0531	34.5789	37.4053	39.3226
Rolling plains	11.3832	3.8305	-	13.6666	25.9938	18.8920	23.0231
Hills	-2.9773	-	-	-	-	-	-
Mountains	-45.0794	-45.3842	-	-	-	-	-
Rugged mountains	-	-	-	-	-	-	-
Extremely rugged mountains	-	-	-	-	-	-	-

Conclusions: The comparison of measured and modeled one-way pattern-propagation factors indicates significant differences, particularly as a function of the method chosen by ALARM to determine the one-way pattern-propagation factors. The overall impact of these differences on the prediction of maximum target detection is significant if a clear line-of-sight exists between the radar and the target. If the target is masked from the radar, the impact is insignificant.